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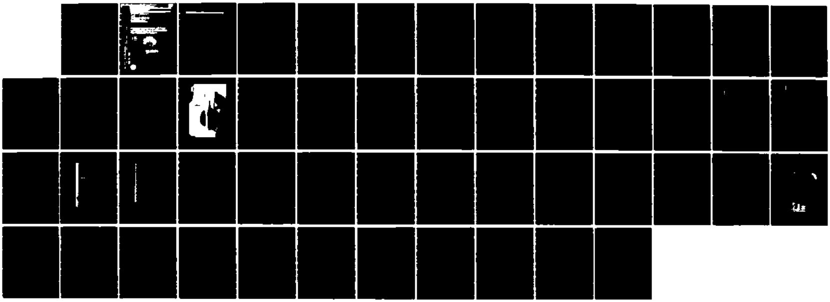

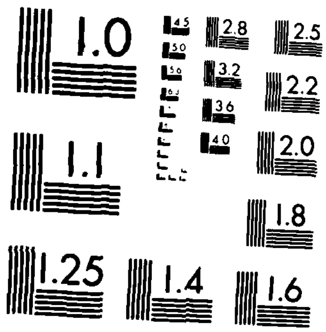

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Ship Performance Department
Research and Development Report

Evaluation of Liquid Crystals, Dot Fluids, and Compliant Coatings for Hydrodynamic Flow Visualization on Surfaces

by
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J. P. Sikora

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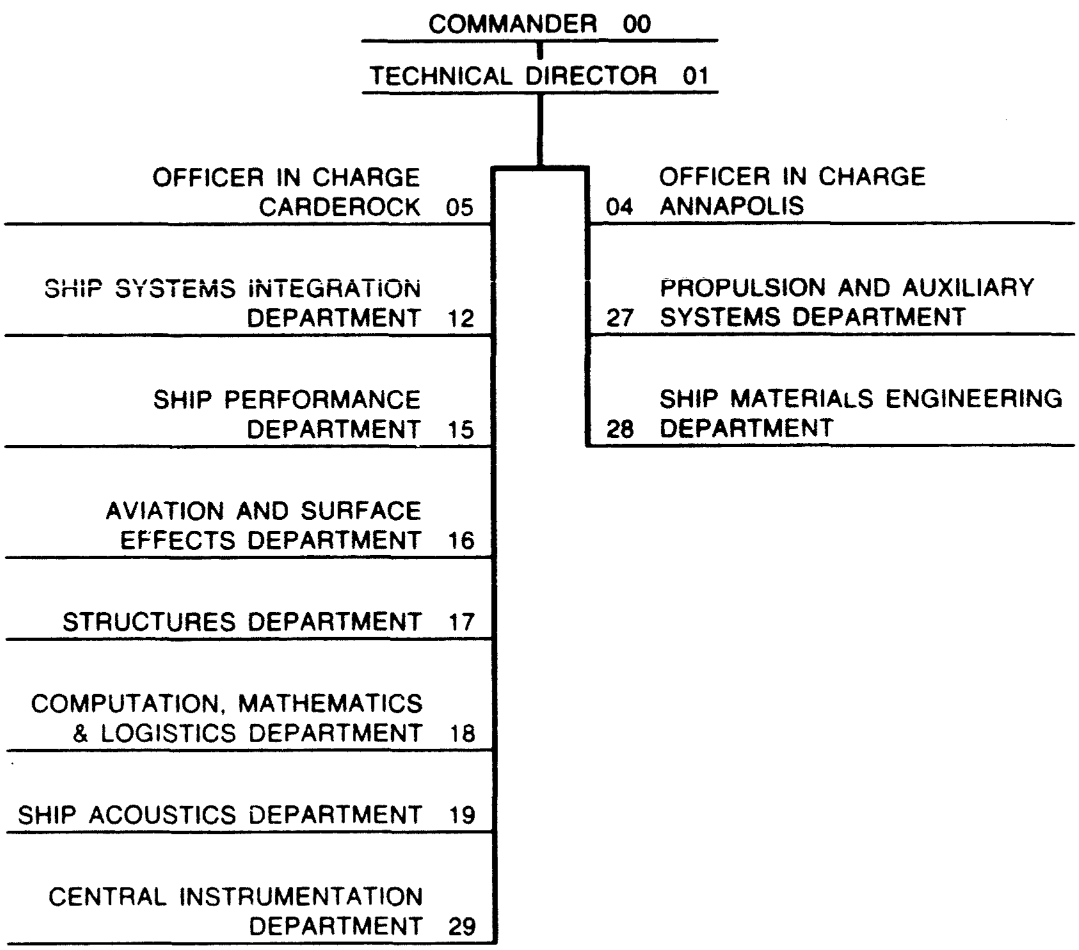

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Three new approaches to hydrodynamic flow visualization on surfaces were evaluated: shear-sensitive liquid crystals, high-viscosity dot fluids, and optically monitored compliant coatings. Liquid crystal mixtures were highly successful, producing high-resolution observations of both steady and unsteady boundary layer separation and transition characteristics. Dot fluids of high viscosity were not superior to low-viscosity fluids thickened with pigment, but minor differences in behavior occurred among the four base fluids used. Optical methods of detecting shear- or pressure-induced displacements of compliant coatings were unsuccessful in a water tunnel environment.

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ABSTRACT

Three new approaches to hydrodynamic flow visualization on surfaces were evaluated: shear-sensitive liquid crystals, high-viscosity dot fluids, and optically monitored compliant coatings. Liquid crystal mixtures were highly successful, producing high-resolution observations of both steady and unsteady boundary layer separation and transition characteristics. Dot fluids of high viscosity were not superior to low-viscosity fluids thickened with pigment, but minor differences in behavior occurred among the four base fluids used. Optical methods of detecting shear- or pressure-induced displacements of compliant coatings were unsuccessful in a water tunnel environment.

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INTRODUCTION

When one hears the term "flow visualization", usually images spring to mind of clouds of dye (in water) or smoke (in air) meandering in vortex-shaped trails. Many other injection and visualization techniques are available as well for revealing flow field patterns. This report does not deal with any of those "flow field" techniques. Instead, approaches strictly limited to visualizing surface flows (flows immediately adjacent to a body surface) are described. These techniques enable one to determine certain qualitative and possibly quantitative boundary layer characteristics: transition, separation, and possibly direction and magnitude of shear stress at the surface. A further limitation is that only techniques useful in water are explored here.

Much useful information can be gained from even a qualitative knowledge of surface or boundary layer flow because forces, wakes, and other fluid-body interactions often critically depend on the nature of the boundary layer flow on a body. Such flow information can enable other measurements to be properly interpreted, which is particularly important when observations on small-scale models are to be projected to large-scale systems.

Although flow visualization (FV) techniques are being used more widely in research work as time goes on, virtually no hydrodynamic research routinely utilizes a surface FV technique (generally a coating) when no specific objective calls for it. Available techniques, though of some effectiveness, have many deficiencies which reduce their usefulness. These deficiencies variously include facility contamination, premature activation, inadequate resolution, long recycling time, and difficulty of installation.

It is noted that there have been relatively few published advances in surface FV techniques, particularly in water, over the past several years, compared to the numerous advances in flow-field visualization techniques. Even the considerable research activity in turbulent boundary layer flow has employed only dye injection or tracer particles rather than some form of material attached to the surface. These approaches reflect interest in microscopic flow structure rather than in identifying

macroscopic flow features. Monitoring such macroscopic features is a qualitative task which can yield considerable insight into the nature and prediction of forces acting on a body.

The objective of the present work was to identify new technological approaches which avoid some of the deficiencies of existing surface FV techniques. New techniques were sought which could be adapted easily to a wide range of experiments, thus promoting routine use.

In order to identify new FV techniques, a general overview of typical experimental goals was conducted. Knowing these goals, FV performance requirements were drawn up. Several FV techniques were identified which either currently met these goals (existing techniques) or potentially could be viable techniques (new techniques). The methods were as follows:

Existing Techniques	*New Techniques*
Oil dots and film	Shear-sensitive liquid crystals
Lead-acid paint	Compliant coating speckle photography
Tufts and minitufts	Compliant coating holography
Flow flags	
pH paint	
Oil film interferometry	
Pressure-sensitive laminate	

The above techniques were considered as candidates for improved technology. All three new techniques offered promise of permitting very detailed surface distributions of shear stress or pressure to be determined. However, experimental verification of these untried approaches was required. Among the existing techniques, all had serious limitations. A method of overcoming the principal limitation of oil dots and films (namely, permature flow) was proposed: using an inherently high-viscosity fluid rather than low-viscosity fluid heavily loaded with pigment. No potential improvements were identified for any of the other existing techniques. Thus, four new or revised FV techniques required evaluation.

This report describes the evaluation of those four new approaches:

Shear-sensitive liquid crystals
Compliant coating speckle photography
Compliant coating holography
Oil dots using high-viscosity fluids.

Evaluations were performed by applying the coating associated with each technique to a faired strut installed across the jet of a moderate-speed water tunnel. Operating conditions are described in the sections of this report describing each technique. The existing FV techniques listed above are documented in the Appendix for the benefit of researchers who might not be familiar with all of them.

CURRENT EXPERIMENTAL RESEARCH OBJECTIVES

EXPLICIT OBJECTIVES

To a large extent, the objectives of flow experiments conducted in naval and related facilities are to achieve smooth, unseparated (for low drag), non-cavitating flow over (usually) closed bodies, including attached appendages. Additionally, it is desired that transition from laminar to turbulent boundary layer flow occur at a known location, usually near the transition location of a full-scale prototype of the model being tested. In addition to direct observations of these characteristics on scale models, validations of theoretical analyses are often required.

The following examples of the above objectives are provided for illustration: on large models of surface ship hulls, alignment of bilge keels, various support struts, rudders, and anti-roll fins is performed using flow direction on and near the hull. On propeller blades, regions of separation, extent of laminar vs. turbulent flow, and directions of skin friction (indicating differences between potential flow and actual flow), are needed. Research into relationships between boundary layer flow and cavitation inception is conducted using headforms having transition stimulation devices, and the location of natural transition may be observed on many types of models. The behavior of vortices in proximity to model surfaces is also studied with FV techniques.

IMPLICIT OBJECTIVES

The explicit objectives described above may be reduced to determining a number of characteristics of the boundary layer, and/or the pressure distribution on model surfaces. These characteristics are:

Characteristics	*Application*
Shear stress direction	Alignment of keels, struts, control surfaces; validation of propeller design predictions; detection of separation; vortex behavior
Shear stress magnitude	Detection of transition and separation; vortex behavior
Pressure (steady and unsteady)	Detection of cavitation inception and separation; validation of pressure distribution predictions

Determination of these surface flow characteristics is complicated by the wide range of speed, ambient pressure, model shape and size, facility access, and type of motion within which typical models are operated. Thus, techniques which can be adapted to a wide range of conditions must be given priority. An indication of the range of skin friction magnitude and pressure magnitude experienced by a 20-ft (6.1-m) long submarine model at typical model speeds is given in Figure 1. Analogous plots for a propeller blade would show values between one and two orders of magnitude larger. A further variable influencing some observations (transition-related pressure spiking, propellers in nonuniform wakes, vortex shedding) is unsteadiness of the pressure and skin friction.

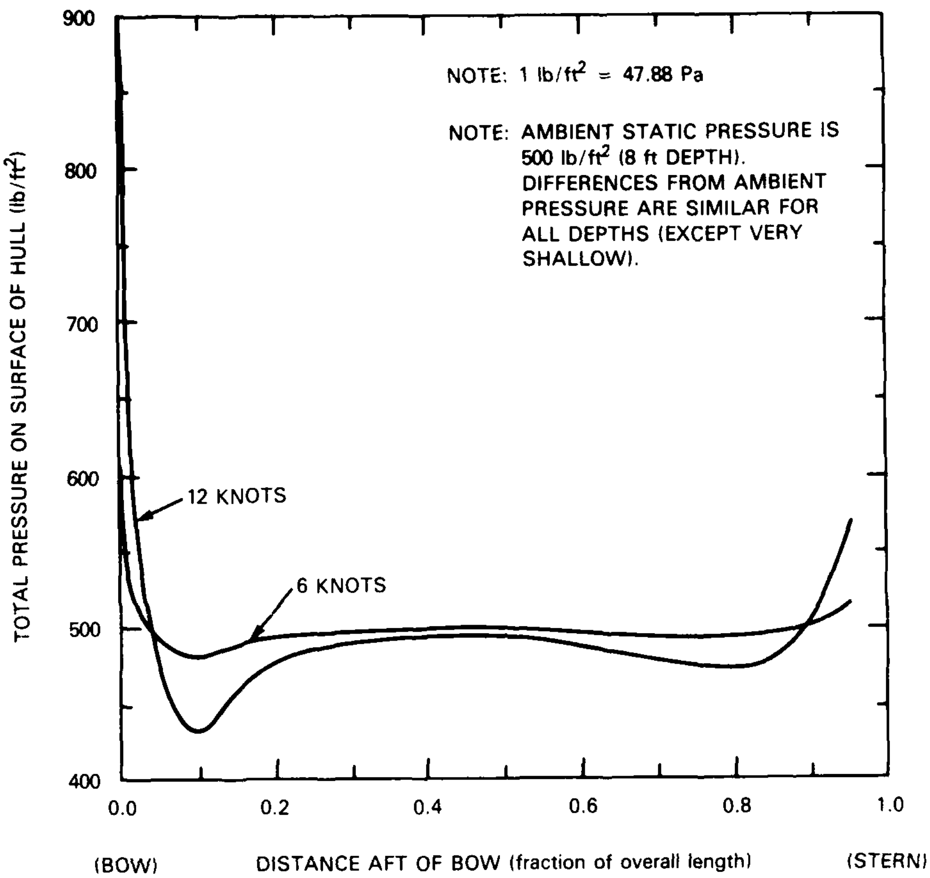


Fig. 1a. Surface pressure distribution.

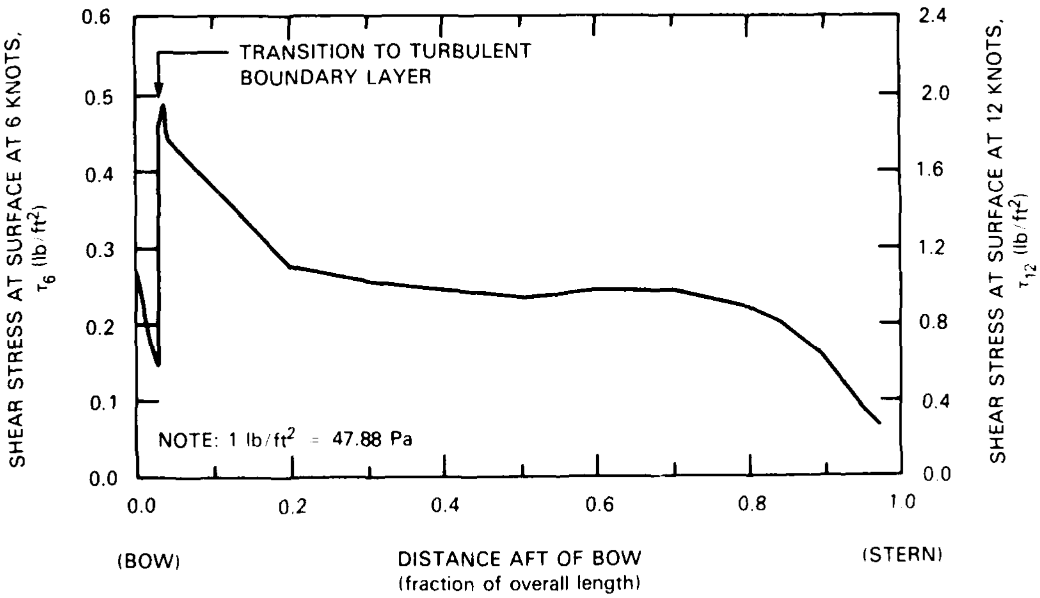


Fig. 1b. Surface shear stress distribution.

Fig. 1. Hydrodynamic pressure and shear stress calculated to occur on the surface of a submarine model.

It is noted that to some extent the operating conditions of a model may be altered to accomodate requirements of FV. Variations usually involve lower speed (skin friction magnitude) to permit dye injection under laminar conditions. It would be acceptable in some cases to operate a model at lower or higher speed or at a different static pressure to match the sensitivity range of a particular technique.

REQUIREMENTS FOR ACCEPTABLE TECHNIQUES

The above objectives have been rephrased into a list of design-type requirements which are given below.

PERFORMANCE REQUIREMENTS OF FV TECHNIQUES

1. Information is required on one or more boundary layer flow parameters related to performance of hydrodynamic models. These parameters include:
   a. shear stress direction
   b. shear stress magnitude
   c. pressure magnitude

   The information may be either quantitative or qualitative, and must apply to the run condition of interest rather than reflecting flow startup or shutdown. Both spatial and temporal variations are of interest.
2. Information is required at a large number of closely spaced points, or in a continuous distribution, rather than at a small number of points. Thus, high "resolution" is required, with resolution measured in terms of the number of values (of shear stress or pressure direction or magnitude) observable per unit area.
3. The technique cannot significantly interfere with (alter) the natural flow around model.
4. The technique must be either semi-permanent (remains on model after removal from facility) or transient, i.e., reversible (changes with flow). Transient is preferred.
5. The technique must yield photographic patterns, in situ if transient.

ENVIRONMENTAL REQUIREMENTS FOR FV TECHNIQUES

The technique must function on the surfaces of models in hydrodynamic facilities under at least some of the conditions described below.

1. Models are immersed in water flow under mounting arrangements which often require long periods of time (up to 2 h) to remove the models from the water. The models are
   a. suspended beneath towing carriages, at depths of zero to 35 ft;
   b. in closed circuit water tunnels, at gage pressures from -1 to $+4$ bar;
   c. from 1 in. to 30 ft in streamwise length;
   d. operated at speeds from 1 to 50 knots with principal interest directed toward large models at about 10 knots and small models at 20 to 50 knots;
   e. either towed in a straight line or rotated as in propellers

2. Model surface shapes are not developable. Surfaces in some cases must be hydraulically smooth; in other cases, slight roughness may be tolerable. Techniques need not extend fully into sharp corners and around sharp edges to be useful.
3. Introducing foreign substances into the facility water is discouraged, unless easy removal is feasible.
4. Materials should be nontoxic and not a health hazard to test personnel.
5. If medium is semi-permanent, it must be quickly recyclable to permit continued testing.

DESCRIPTION OF TEST BODY

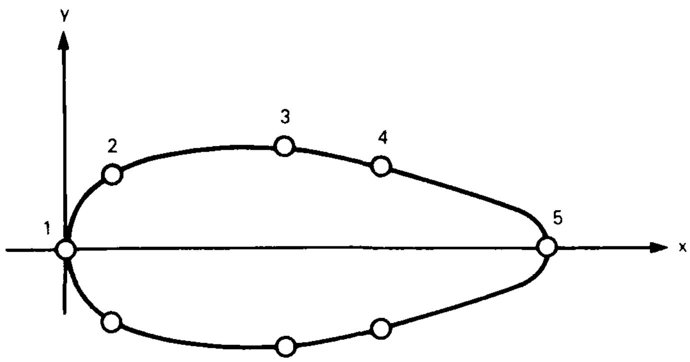
All FV technique evaluations were performed using a long strut-like tube mounted vertically across the jet of the DTNSRDC 12-Inch Variable Pressure Water Tunnel.[1] The tubing had been manufactured with shape specified in Mil Std 33534 (ASG) and is designated MS33534(ASG)-S32 Streamline Tubing. The cross sectional shape, shown in Figure 2, can be characterized as a 40% thick blunt-nosed foil, the trailing edge of which has been radiused to make a 42.4% actual thickness ratio. All observations were made with the foil at approximately zero angle of attack.

The foil was mounted semi-rigidly in the water tunnel test section; looseness was not noticeable to the touch. The upper end was bolted to the tunnel hatch cover, which was tightly clamped to the tunnel with a rubber gasket separating the two surfaces. Thus some softness was present at this end. The lower end was bolted to a pipe which was inserted snugly into a drain pipe opening at the bottom of the test section. While the potential for motion was present, any motion that occurred from these attachments was not visible in video or motion pictures. Vibration measurements are presented in the section describing optical techniques.

The foil surface was coated with several types of paint, liquid crystal material, dot fluid, and compliant foam as will be described for each FV technique.

Flow speeds used during testing ranged from 3.1 to 14.6 knots (1.6 to 7.5 m/s).

The qualitative boundary layer characteristics on the test model, shown in Figure 3, are known in great detail as a result of the FV testing. In contrast to data available for most test bodies, even the time variations in the location of transition were observed. These characteristics were determined primarily with the liquid crystal coatings. An extensive region of laminar flow existed over the forward part of the foil. A highly unsteady transition region occurred near midchord, with turbulent flow continuing aft to separation near the trailing edge. Locations of transition and separation varied with speed. Transition was predominantly located at a line ranging from 0.55c (55% of chord (c)) aft of the leading edge at 7.1 knots to 0.39c at 14.6 knots. From this location, transition moved forward rapidly, and receded in irregular areas over spanwise distances of perhaps 0.1 to 2 chords. The forward movement appeared to be as much as 0.25c at lower speeds and 0.1c at higher speeds. Separation moved aft from 0.88c at 7.1 knots to 0.94c at 14.6 knots. Further discussion of the boundary layer behavior is included in the section on liquid crystal coating performance.



POINT	x in. (mm)	y in. (mm)
1	0	0
2	0.2697 (6.85)	0.4115 (10.45)
3	1.2137 (30.83)	0.5715 (14.52)
4	1.7531 (44.53)	0.4580 (11.63)
5	2.6970 (68.50)	0

MAXIMUM THICKNESS = 1.143 in. (29.03 mm)
TRAILING EDGE RADIUS = 0.217 in. (5.51 mm)

Fig. 2. Nominal dimensions of foil cross section.

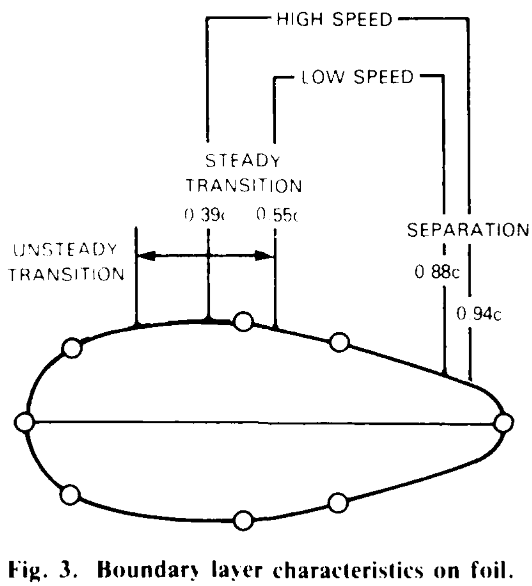


Fig. 3. Boundary layer characteristics on foil.

LIQUID CRYSTAL COATINGS

Liquid crystals have been described as the most optically active form of matter.[2] As such, their properties must be considered as a potential source of surface flow visualization, especially since only a microscopic layer of the material is required. Among the many physical effects which produce optical changes in liquid crystals are temperature and shear stress. Both of these effects have been used for flow visualization in air flow. Recently, two successful applications of temperature-sensitive liquid crystals in water hae been reported. Ogden and Hendricks[3] employed microencapsulated liquid crystal protected by a waterproof plastic coating which transmitted temperature variations sufficiently well to indicate time-varying turbulence patterns on the surface of a heated body. This method is primarily applicable to surface heat-transfer observations rather than shear stress observations, except when changes in boundary layer characteristics caused by the heating are either under study or prove to be small. Rhee *et al.*[4] used liquid crystal microcapsules as thermally indicating tracer particles in a flow field study. Thus, neither approach constituted the surface FV technique being sought in the present work.

As an alternative approach to a solid barrier-like coating, we explored several additives which offered promise of increasing the water resistance of liquid crystal mixtures without reducing their ability to sense flow-induced shear forces.

LIQUID CRYSTAL CHARACTERISTICS

Liquid crystals are organic compounds with "properties intermediate between those of a true crystal and those of a true liquid."[2] Some liquid crystals have optical properties that change under varying shear stress. The mechanism by which shear stress produces optical changes in one type of liquid crystal, the cholesteric type, has been described by Brown and Crooker.[2] In this material, molecules of helical structure selectively polarize and reflect the specific wavelength (color) corresponding to the pitch of the helix. Physical forces alter this pitch and change the wavelength that is selectively reflected, thus changing the color of the material.

Cholesteric liquid crystals were chosen for the present work, following the previous investigation of Klein and Margozzi.[5] This previous work provided a wide range of information on the properties of three mixtures of four cholesteric liquid crystals. The mixtures had strong (but nonlinear) sensitivity to shear, low to moderate temperature sensitivity, and resistance to crystallization (solidification) for up to 24 h at room temperature.

One of the mixtures developed in the earlier work was selected for the present investigation. The mixture had the following composition:

Liquid Crystal	*Proportion (%)*
Cholesteryl nanoate	60
Cholesteryl chloride	30
Cholesteryl benzoate	5
Cholesteryl oleyl carbonate	5

This mixture will be referred to as LC-12 following the earlier terminology.

Calibrations of reflected color as a function of shear stress were presented by Klein and Margozzi[5] for one of their mixtures (not LC-12). It was found that the color ranged from green to yellow at low shear stress (up to 300 Pa), but changed slope and returned toward the blue-green area of the light spectrum at higher shear values. LC-12 was described as having greater color sensitivity at low values of shear (50 Pa), attaining a red color before cooling may have caused a return to the green range. It is presumed that LC-12 also reverses its sensitivity and shifts toward the blue above some low shear value in the neighborhood of 50 Pa.

A second candidate liquid crystal material was also used. This material was procured commercially and was described by the vendor as merely a shear-sensitive liquid crystal.

In the present investigation no quantitative calibrations were made. However, subjecting either the LC-12 or the commercial liquid crystal to a high but undetermined value of shear by squeezing it between a rotating glass stopper and bottle neck produced a deep blue color. Values of shear stress calculated to occur on the hydrofoil model ranged up to about 50 Pa.

COATING COMPOSITION

In an attempt to produce a liquid crystal having good resistance to water-induced erosion, contamination, or other deleterious effects, the two liquid crystals were mixed with various additives listed in Table 1. Nine additives in various proportions were used with LC-12, and one additive was used with the commercial liquid crystal. Additionally, each liquid crystal was employed in its pure state, without additive.

The general method of preparing the mixtures containing liquid crystals with additives consisted of dissolving the previously compounded liquid crystal mixture in diethyl ether. An appropriate amount of additive was introduced such that the final desired weight percentage of additive was present. The mixture was stirred until the solution was homogenous. The solvent was removed under reduced presure, and the final traces of solvent were removed under high vacuum (0.01 to 0.1 Torr). The resulting viscous mixtures were suitable for testing without further treatment.

All coatings were satisfactorily applied with a small brush, and pure LC-12 was successfully applied by spraying it in a solution of ether. Brushing produced a thick coating with distinct brush marks and far more material than was applied by spraying. The sprayed coating was deliberately kept thin.

Maximum visibility of the colors reflected by liquid crystal is obtained when the material is applied over a nonreflective black surface. For the present experiment, a flat black, silicone-acrylic enamel was applied to the foil model as a background for the liquid crystal.

COATING PERFORMANCE

Test runs proceeded by immersing the foil, which had been coated with one, two, or three coating samples, in the water tunnel for about 10 min before flow began. Flow speeds were then maintained in typical patterns of 3.5 knots for about 5 min, 7.1 knots for about 10 min, 10.7 knots for about 10 min, and 14.6 knots for about 10 min. Intervals of time varied up to 30 min.

Table 1. Liquid crystal coating formulations.

Designation	Liquid Crystal	Additive	Method of Application
C1	LC-12	None	Brush
C1		None	Spray
C2		20% Hexadecanol	Brush
C3		5% Hexadecanol	
C4		10% Hexadecanol	
C5		10% Carbowax	
C6		20% Carbowax	
C7		10% Hexadecylstearate	
C8		5% SE-30	
C9		10% Tetradecanol/ 10% Trimyristin	
C10		10% Silicone fluid	
C11		Stearic Acid	
C12		10% Hexadecanol/ 10% Hexadecylstearate	
C13		20% Trimyristin	
C14	Commercial	None	Brush
C15	Commercial	20% 2-Phenyl-1,3-Propanediol	Brush

All observations were made visually by color video camera or high speed motion picture camera, and by still camera. Viewing through a clear acrylic window was enhanced using a single photographic floodlight and electronic flash.

General Behavior

Most of the coating formulations were effective in indicating various regions of boundary layer flow. Most coatings exhibited a wide range of color during periods of water flow. Color variations and texture variations usually enabled determination of regions of laminar and turbulent flow, as well as separation lines and unsteady transition behavior. Various characteristics of the coatings are described in the following sections.

A color photograph of three coatings under test conditions is shown in Figure 4. It is emphasized that neither the photographs made during the experiment, nor the video recordings, nor the motion picture film, captured the extraordinary intensity and color range seen by eye. Partially color-blind individuals were not able to appreciate the full color range either. Time variations in color were successfully recorded by both video and motion picture.

The photograph shows materials ranging from excellent to poor in performance. The center material (C15) was excellent; the upper material (C14) had excellent color range but was poor in other respects; and the lower material (C12) was typical of the worst-performing coatings tested. A detailed discussion of the materials' performance is given in the following paragraphs.

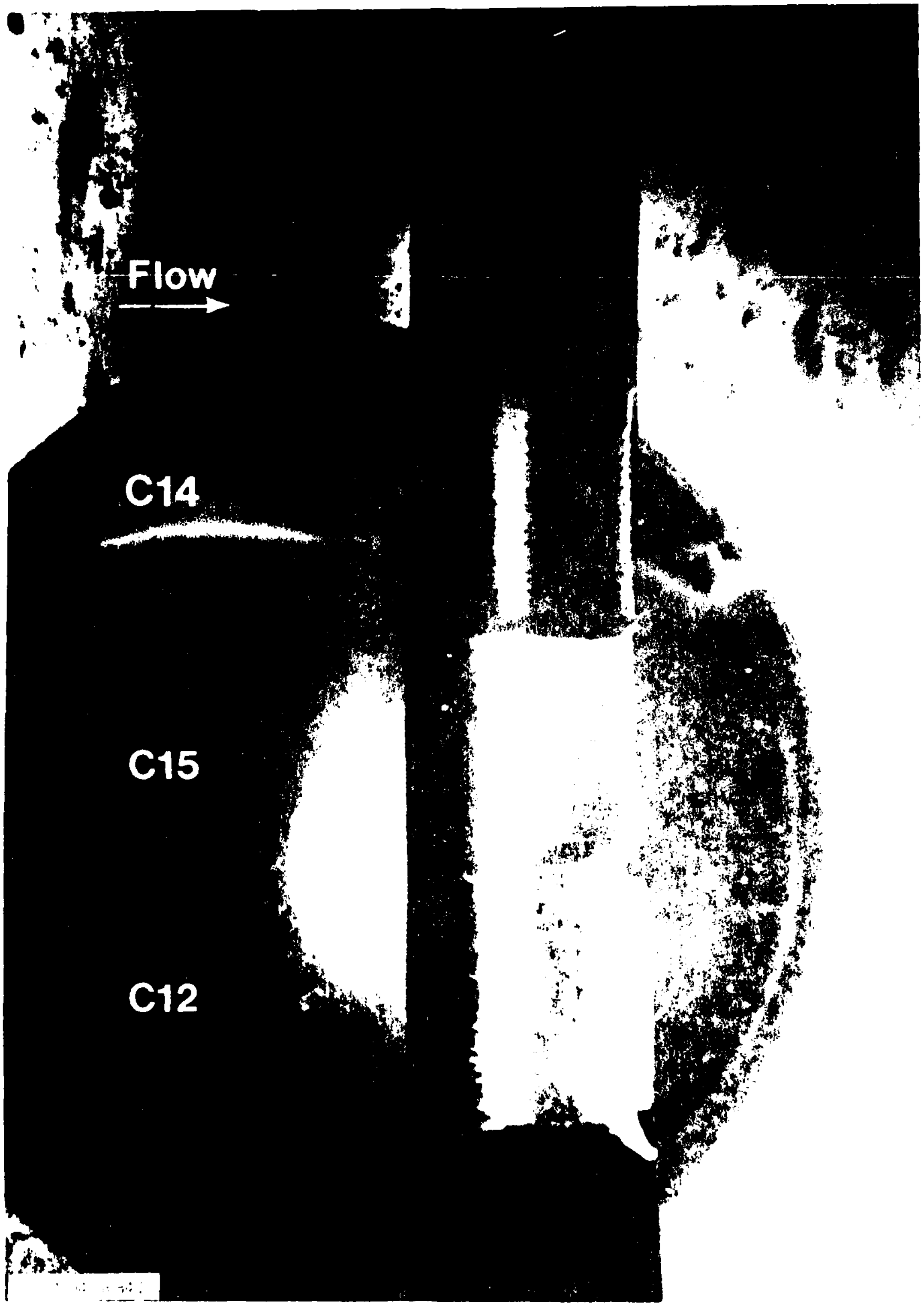


Fig. 4. Photograph of three liquid crystal coatings on hydrofoil model in the 12 in. water tunnel.

Mobility

The term mobility refers to the tendency of the liquid crystal material to flow downstream along the model surface. Generally the coatings exhibited four stages: immobility with uniform color, mobility with brightly color-contrasting wavelets, bright color contrasts (including unsteady flashes of color) with no mobility, and faded color contrasts (including unsteady colors). Mobility took the form of downstream spreading of the painted-on coating, with buildups of the oil-like liquid in regions of low shear stress. There were two such regions: in the aft part of the laminar flow region, just forward of midchord, and along a separation line just forward of the trailing edge.

Particularly noticeable in terms of mobility was the effect of increasing speed at low and medium speeds. Each new, higher speed (3.5, 7.1, 10.7, and 14.6 knots) produced a more forward transition location. Since relatively high shear stress occurs immediately aft of transition, the increased shear on the built-up coating material just forward of the original transition line drew large amounts of liquid crystal aft into the turbulent region in either separate rivulets or, less commonly, continuous sheets. These rivulets were brightly colored, usually against a dark background (dark when viewed from opposite midchord).

Mobility effects were undoubtedly a result of having applied a thick coating. One test of a thin coating (C1) sprayed on by atomizer resulted in greatly reduced mobility, with other performance characteristics similar to the brushed-on material although color was somewhat less intense.

These observations closely parallel those describing behavior of coatings used by Klein and Margozzi[5] in an aerodynamic pipe flow. That investigation concluded that roughness occurring on the coating surface was unacceptable. On the present hydrofoil model, the most noticeable wavelike roughnesses usually disappeared after an initial period of flow on coatings having smooth texture, as described in the paragraph below entitled Fineness of Texture. The general tendency was for the material to become smooth-looking as time passed, except at the trailing edge separation line where a definite, brightly-colored ridge was visible. Material remaining on the model after testing was visually very smooth, judging by reflected light. Residues were extremely weak in color, or transparent, and resembled a thin coat of wax or a grease stain. One did not get the impression that the fully spread-out coatings would alter the natural boundary layer flow.

Color Range

Colors usually ranged over green, gold, orange, and blue, with mixtures of these, and occasional reddish orange. Examples of these color patterns are shown in Figure 4.

Superimposed on the colors were textural shadings reminiscent in some cases of fish scales. These textural features also included long streamwise lines of bright color in the turbulent region.

The materials ranged from good to poor. Good materials showed a full range of orange, gold, green, and blue. Average materials showed those colors but somewhat faded. Poor materials had grayish tan backgrounds with blue showing only on traveling wavelets.

Dynamic Response

Superimposed on the above characteristics was an extraordinary temporal variation of coating color in the region just forward of midchord. These color changes, termed "flashing," were nearly always composed of bright blue regions which moved forward from the predominantly turbulent region into the predominantly laminar region. Differences in appearance of the two regions resulting from different coating thicknesses, texture, and presumably levels of shear stress led to considerable contrast between the flashing regions and the surrounding nonflashing regions. The behavior showed coherence over spanwise lengths of up to 2 chords. This degree of coherence, extending even over different coating samples, implies strongly that local roughness in the coating was not triggering transition locally.

Much of this dynamic behavior was effectively recorded on videotape and on one high speed motion picture. Comparisons during the testing showed, however, that video did not capture the full resolution, angular dependence, and brightness of color evident to the direct observer.

Angular Sensitivity

Dimensions of the tunnel window permitted a maximum variation of 67° in viewing and illuminating the model. Both lighting angle and viewing angle had an effect on surface brightness. These effects were not studied in depth. It appears that the most effective illumination is directly behind the viewer. The best coatings permit lighting and viewing from different angles so as to reduce glare and make a wider portion of a curved model viewable from one viewpoint.

Some coatings developed extremely smooth finely-textured surfaces which appeared dark when viewed at angles other than 90°. Other coatings had brighter colors over a fairly wide range of angles.

Fineness of Texture

Fine texture is a desirable quality from the standpoint of resolution. Textural differences ranged from extremely small or even uniform regions of color, to coarse-grained scaly surfaces. The worst textures corresponded to material that was too viscous to become smooth even after lengthy exposure to high speed flow.

Adherence of Coating

In most cases the coating flowed aft, accumulated at the trailing edge separation line, and was washed into the water in small globules over a period of several minutes. However, a moderate thickness of material was generally left on the originally coated surface. This coating tended either (1) to remain colorful over long flow times (8 to 10 min or longer) at high speeds, (2) to become extremely thin, resulting in weak color, or (3) to wash off entirely from the leading edge aft.

It is noteworthy that many materials adhered so well to the painted surface that after testing, forceful rubbing with a dry paper towel was required for removal. The most tenacious residues were produced by pure LC-12, carbowax, stearic acid, hexadecanol, and silicone fluid.

Coating Effectiveness Rating

Comparisons were made among the different materials in terms of four of the above parameters: color range, angular sensitivity, texture, and adherance. Numerical ratings were given in each category and summed for a total score, with color range being weighted twice as much as the other three categories. The tabulated results are shown in Table 2.

Several coatings were rated very highly. Differences among these materials were confined to variations in angular sensitivity and texture, which were usually negatively correlated. Thus, in selecting a coating, one could accept high angular sensitivity (lower rating) if a wide field of view were available, so as to obtain the finest texture for maximum resolution of flow features, or select a lower angular sensitivity if the surface were being studied from a limited range of angles, such as by a fixed camera, while accepting slightly coarser texture.

Evaluation of Additives

Several observations can be made regarding the effectiveness of the additives used to improve water-resistance of the liquid crystal base materials. LC-12, used in its pure state, performed extremely well in nearly all respects. None of the additives used with this material produced any improvement in adherance or in overall rating. However, the additives did affect the performance of LC-12 in various ways, improving or worsening one or more characteristics. On the other hand, the commercial liquid crystal did not adhere well in its pure state. It had a greatly improved adherance, along with reduced angular sensitivity, when mixed with the one additive used. The effects of some additives are detailed in the following paragraphs.

Hexadecanol - This additive is a saturated aliphatic alcohol and was selected with a view to its solubility in liquid crystals in one portion of the molecule and solubility in water at the opposite end. It was hoped that this would enhance the interaction between the LC and moving water at a molecular level. The additive was tested at three concentrations: 5, 10, and 20% (by weight). The ability of the LC to adhere to the model surface showed no dependency on concentration in the range tested. The lowest concentration exhibited poorer texture, whereas the highest concentration showed reduced angular sensitivity (Table 2). It would seem that lower concentrations do not provide enough additive to allow uniform distribution of hexadecanol, and the highest concentrations break up the intermolecular interactions that give rise to optimum color response.

Carbowax 20M - This material is a polar polymer of polyethyleneglycol. This substance gives good color response and angular sensitivity only at relatively high concentration, although it exhibits poor texture. Some intermediate concentration would likely give an optimum performance. The poor texture appears to result from failure of the high concentration to spread out and become smooth, as other materials did. It is hypothesized that operation at higher speeds would produce a smooth, finely textured coating.

SE-30 - This polysilicone polymer is nonpolar and is soluble in water. This material apparently minimizes the molecular interaction of the water molecule with the LC, serving to insulate the LC from the water. This is manifested in a poor shear response characterized by poor color, sensitivity and texture. It is unlikely then that

Table 2. Coating effectiveness in 7- to 15-knot speed range.

Coating	Color Range	Angular Sensitivity	Texture	Adherance	Total
C1	6	3	2	3	14
C15	6	3	2	3	14
C4	6	2	3	3	14
C8	6	2	2	3	13
C6	6	3	1	3	13*
C2	6	1	3	2	12
C9	6	1	3	2	12
C10	4	3	2	3	12
C5	4	2	2	3	11
C7	4	2	2	3	11
C3	4	3	1	2	10
C14	6	1	2	1	10**
C13	1	3	2	3	9
C12	1	3	1	3	8
C11	1	3	1	1	6

Note: Good = 3 points, Average = 2 points, Poor = 1 point. Ratings weight color range twice as heavily as other characteristics.

*Coating C6 may have a finer texture if used at speeds above 15 knots. The material did not spread out completely in the speed range used.

**Coating C14 had relatively poor adherance at high speeds but performed satisfactorily at 3 knots.

nonpolar molecules will make effective additives and, thus, should be abandoned.

Stearic Acid - This was the only material tested which could react chemically with either water or the LC. Overall, this material was the poorest tested. This material can transfer a proton, giving rise to a new chemical species. Undoubtedly, this process occurs, and the resultant, charge-bearing material possesses electrical properties that obviate the desired color response. Clearly, such materials are totally unsuitable as additives and are unworthy of future consideration.

Esters - Two alphatic esters, hexadecyl stearate and trimyristin, derived from glycerol, were tested and found to be of marginal utility. Even though the ester moiety is quite polar, it lacks the ability to hydrogen bond to water with the strength of an alcohol, e.g., hexadecanol. That may, in part, account for the overall weak showing of esters. In passing it should be noted that hexadecyl stearate performed better than trimyristin, although the higher concentration of the latter likely caused a greater disruption of the LC response.

Ester-alcohol mixtures - Two additive mixtures of an alcohol with hexadecyl stearate and trimyristin were examined. In contrast to the mixtures containing only ester additives, the trimyristin admixed with alcohol was substantially better than hexadecyl stearate (Table 2). With such limited data, the cause of this reversal is mere speculation. The greatest difference is reflected in the color range. Additional testing involving different additive mixtures (for which data for the pure additives over a larger concentration range are also known) is the logical direction to take to resolve such apparent contradictions.

DISCUSSION OF LIQUID CRYSTALS

There are two aspects of the liquid crystal coating that provide improved flow visualization capability. The first is the functioning of the coating as an oil film having enormously improved ability to indicate local regions of two-dimensional separation. Separation lines are particularly well shown by brightly colored, fluctuating-color ridges against a darker or differently-colored background (see Figure 4).

The second aspect is the ability to visualize the dynamic behavior of transition. The location of separation as seen in the present experiment consisted of an aft, generally straight boundary beyond which color fluctuations did not move, and a forward color-varying region. It can be deduced that fully turbulent flow began at the aft boundary. The influence of water tunnel flow perturbations is not known. This capability has also been developed by Ogden and Hendricks[3] for heated surfaces.

Quantitative determination of skin friction may be possible using this type of coating, since shear calibrations[5] indicate a linear relation over the range estimated to have occurred on the present model. However, the earlier calibrations were no longer linear at higher values of shear corresponding to blue-green colors. The observed blue color in the transition region implies a much higher value of skin friction which would require more elaborate data analysis.

The liquid crystal material meets all performance criteria described under Requirements for Acceptable Techniques, acting as a transient, high-resolution indicator of shear stress magnitude. The environmental requirements are generally satisfied, although care would have to be used in working with the flammable solvent, and small amounts of the oil-like material were noticed floating on the water surface and would have to be removed by skimming.

This material appears to be a practical alternative to oil film work in water, and presumably in air, which could be packaged in spray-on containers. It should be remembered that the solvent employed, diethyl ether, is highly flammable and explosive in confined spaces.

FLUID DOT TECHNIQUE

As described in the Appendix, pigmented oil coatings and dots work well in water but respond prematurely to flow. Since most fluids currently used are relatively low in viscosity, it was proposed to evaluate a high-viscosity base fluid to determine whether its response would be delayed. In addition, two new (low-viscosity) base fluids were evaluated to determine whether any benefits could be obtained from them.

DOT FLUID MATERIALS

Silicone Fluid

Silicone fluid provided an ideal material for determining the effects of viscosity, because it is available in an extremely wide range of viscosities. The two fluids selected had kinematic viscosities of 10,000 cSt and 100 cSt. A powdered pigment, lampblack, was added in arious amounts to thicken the fluids; concentration ranged from 2 to 18 parts of lampblack per 10 parts of fluid by volume.

Motor Oil

As a baseline for comparisons with conventional techniques, nondetergent SAE 10 motor oil was used with 10 to 20 parts of lampblack to 10 parts of oil.

Fluorinated Ether

Fluorinated ethers are available commercially in a moderate range of kinematic viscosities. The fluids serve as highly inert, noncontaminating lubricants and in other applications. One of the available fluids, having a viscosity of about 1,000 cSt at the ambient temperature used, was selected for evaluation. From 8 to 14 parts of lampblack were added per 10 parts of fluid.

Oleic Acid

Oleic acid is a moderately viscous liquid which is traditionally used as an additive to reduce clumping of titanium oxide particles when suspended in kerosene or other light oil.[6] For the present experiment, oleic acid was used undiluted, along with 17 to 22 parts of lampblack per 10 parts of oleic acid, as a dot fluid.

EXPERIMENTAL PROCEDURE

The selected fluids were mixed with lampblack using personal judgment to produce mixtures which did not sag on a vertical surface under gravity. Usually two levels of pigment were added, with the higher level limited by the need to apply the highly viscous material in the form of small dots without producing excessively long "strings" when the applicator (a small-diameter wood rod) was pulled away from the painted surface.

Dot application, using the wood rod, required a steady hand to touch a drop or piece of mixture to the painted surface, and pull away when the desired dot size was formed. Slow movements were required to permit stretched-out strings of material to snap. Imperfect control of the applicator resulted in variations in dot size and thickness. Different materials also produced different-sized "peaks" of material extending away from the surface.

The dots were applied in vertical rows, making sure that aft dots were spaced between forward ones to prevent running together.

Two types of white paint were used on the model in combination with the dot fluids: oil-based enamel (high gloss) and epoxy enamel (semi-gloss). Small differences were found in the performance of the dot fluids on the two paints, as described in the section Practical Considerations.

During operation of the water tunnel, water speed was raised in increments, usually pausing at 3.1, 7.1, 10.7, and 14.6 knots (1.6, 3.7, 5.5 and 7.5 m/s) for several minutes until the tendency of the dots to elongate was established. In one instance, the tunnel speed was raised directly to the maximum value without pausing. Following tunnel operation, the model was removed from the water after about 5 min.

Most of the testing was recorded on videotape, with still photographs made after removal of the model from the tunnel.

DOT FLUID PERFORMANCE

The dot fluids generally behaved in a manner similar to the conventional motor oil mixture. However, there were several respects in which the fluids differed. One of the most important characteristics was resistance to premature elongation, which could be quantitatively measured. Other observed differences related to the tendency to elongate into well-shaped trails with little spreading of the pigment. Elongation rates, although recorded on videotape, showed a wide variation for each material as a result of skin friction variation along the chord. The wide variation prevented use of this quantity as a descriptive parameter. Actual rates of elongation ranged from zero to perhaps 1 in./s (25 mm/s), with many values concentrated below 0.05 in./s (1 mm/s).

The following four parameters were selected to characterize the dot fluids:

1. *Minimum speed at which trails formed.* This speed, necessarily approximate, distinguishes between lower speeds at which little or no elongation occurred, and high speeds which produced trails significantly longer than the dot diameter.
2. *Degree of taper.* Ideal behavior is production of a narrow trail immediately aft of the dot. Such high taper is good. A poorly tapered trail does not become narrower than the dot, and may even become wider than the dot, as it elongates.
3. *Reliability of elongation.* Dot fluids with good reliability of elongation produced trails from all dots that were applied, at speeds above the elongation boundary. With some fluids, several dots did not elongate at all. Such lesser reliability may have been caused by too little fluid being applied.
4. *Resistance to smudging.* With some fluids, the pattern of trails seen after removing the model from the water had deposits of black pigment spread over the painted surface in both random fashion (with oil) and predominately as pale halos around the trails (with silicone fluid). The best fluids had no visible deposits (called "smudging"). The deposits did not prevent interpretation of the flow pattern, but merely reduced the contrast between the background and the trails to a minor, mostly aesthetic, degree.

Performance of the various dot fluids in terms of the above parameters is summarized in Table 3. Pigment concentrations outside the ranges shown did not perform well. Photographs of typical dot patterns for fluid are shown in Figure 5.

Resistance to Initial Elongation

With respect to elongation resistance, the 10,000 cSt fluid achieved a somewhat higher speed (11 knots (5.7 m/s)) than the 100 cSt fluid (7 knots (3.6 m/s)). However, dots of the higher-viscosity fluid formed poorly tapered dots, as shown in Figure 5d. Fluorinated ether is an intermediate viscosity fluid (1,000 cSt) which also achieved flow resistance up to about 11 knots, with slightly better dot taper. The other low-viscosity fluid, oil (80 cSt), achieved flow resistance to only about 7 knots. The viscosity of oleic acid was not determined.

These results indicate that a higher-viscosity base fluid does produce flow resistance to a higher speed. However, the improvement is relatively weak. Increasing the viscosity from 100 cSt to 1,000 cSt and 10,000 cSt resulted in less than double the speed of initial flow. Adding additional pigment either caused extremely poor taper

Table 3. Performance characteristics of five dot fluids.

Fluid	Volume Concentration (Fluid: Pigment)	Minimum Speed for Elongation (knots)	Taper	Reliability of Elongation	Resistance to Smudging	Recommended Paint	Contraindicated Paint
Fluorinated Ether	10:8 10:14	7 11	Good Fair	Good	Good	Unsanded Epoxy	Sanded Epoxy
Oleic Acid*	10:18 10:22	4 to 7 7	Good Fair	Good	Good	Acid-resistant Surface	Oil-based and epoxy
Motor Oil*	10:10 10:18	n.a.** 7	Good Fair	Good	Poor	Oil-based Enamel	Epoxy
Silicone (10,000 cSt)	10:2 10:10	3 11	Good Poor	Good	Fair	Oil-based and epoxy	none
Silicone (100 cSt)	10:16	7	Fair	Fair	Fair	Oil-based and epoxy	none

*These fluids are known to interact with certain materials which may be present in test facilities. Oleic acid is a strong acid which can attack metals; motor oil can cause damage to rubber seals.

**n.a. = not available.

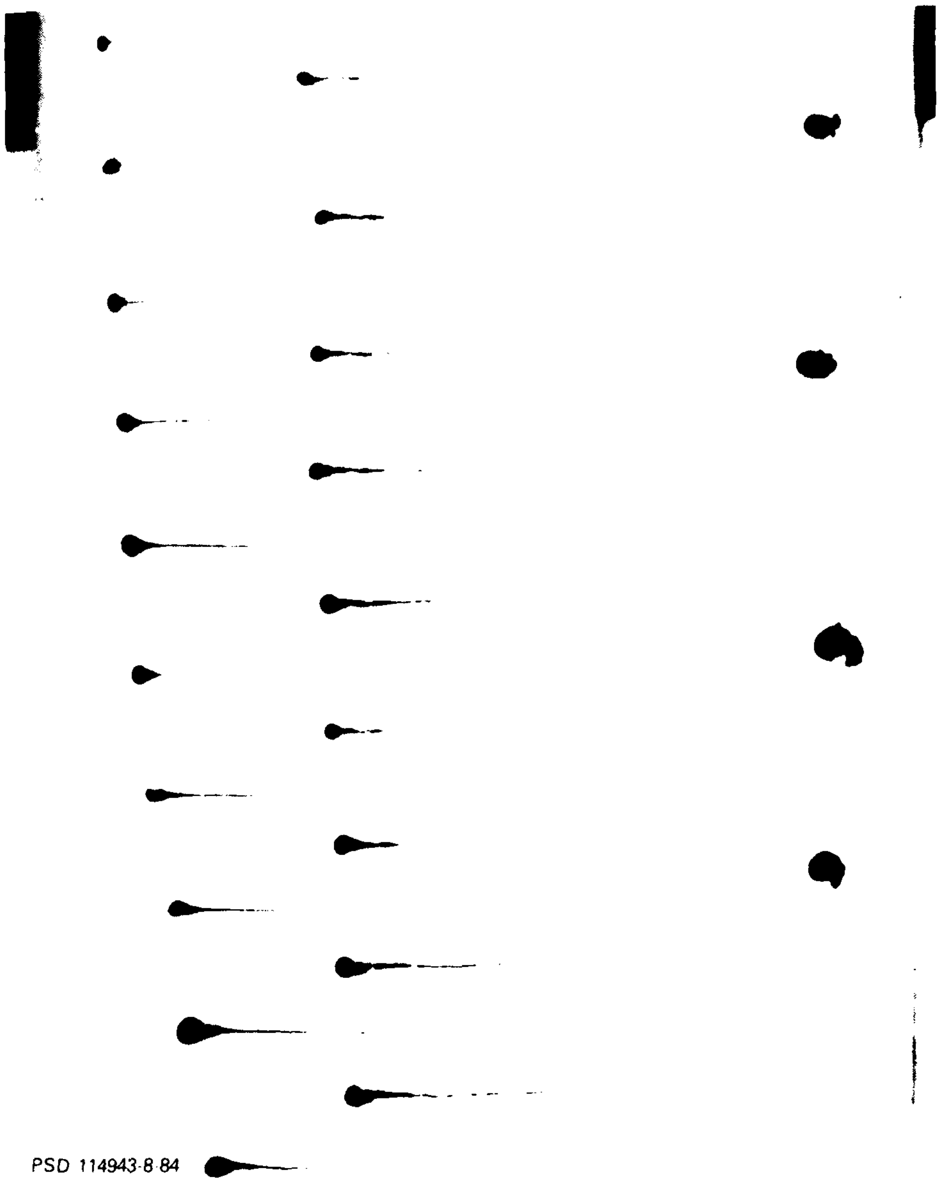


Fig. 5a. Fluorinated ether with 10:8 lampblack on epoxy enamel (unsanded).

Fig. 5. Photographs of dot patterns obtained with five types of fluid.

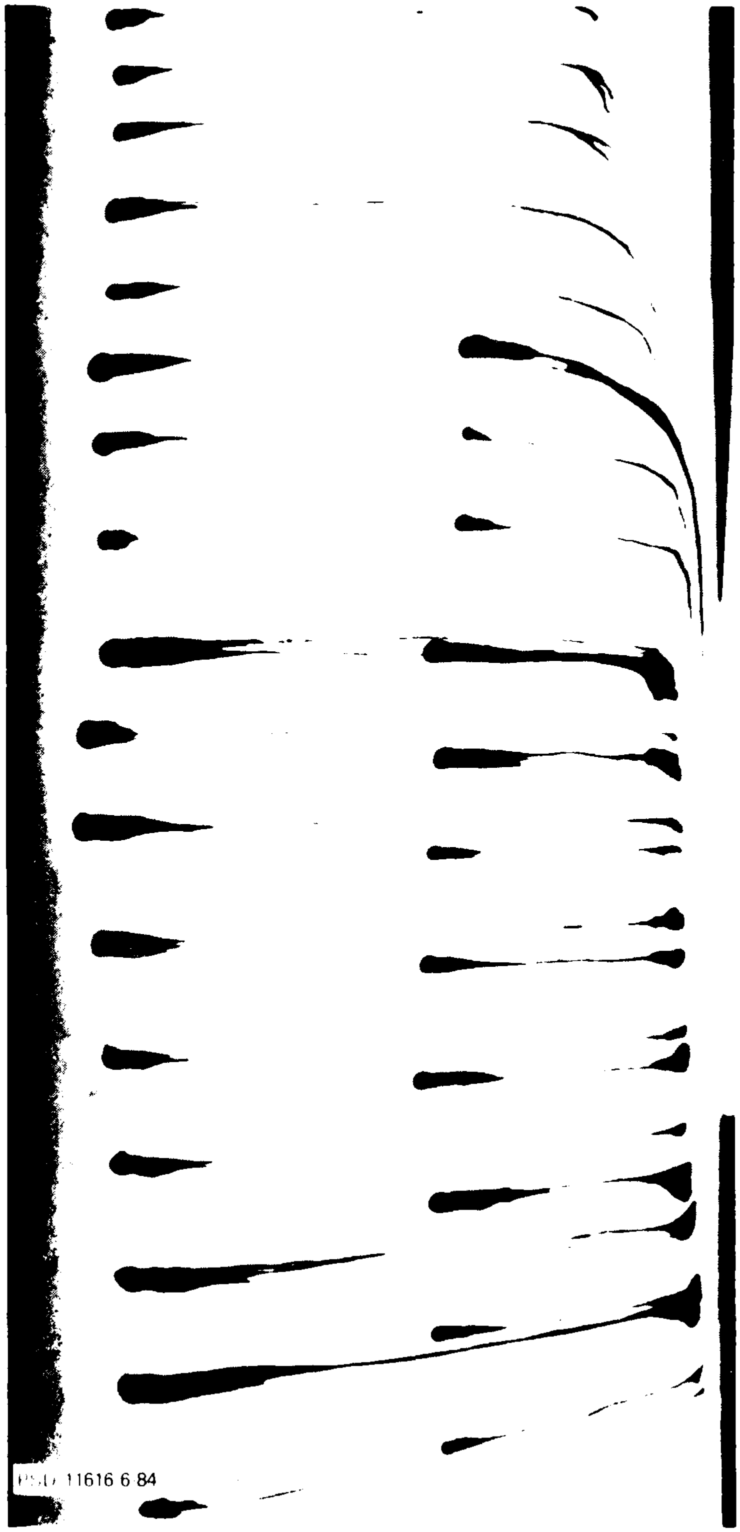


Fig. 5b. Oleic acid with 10:22 lampblack.

Fig. 5. (Continued)

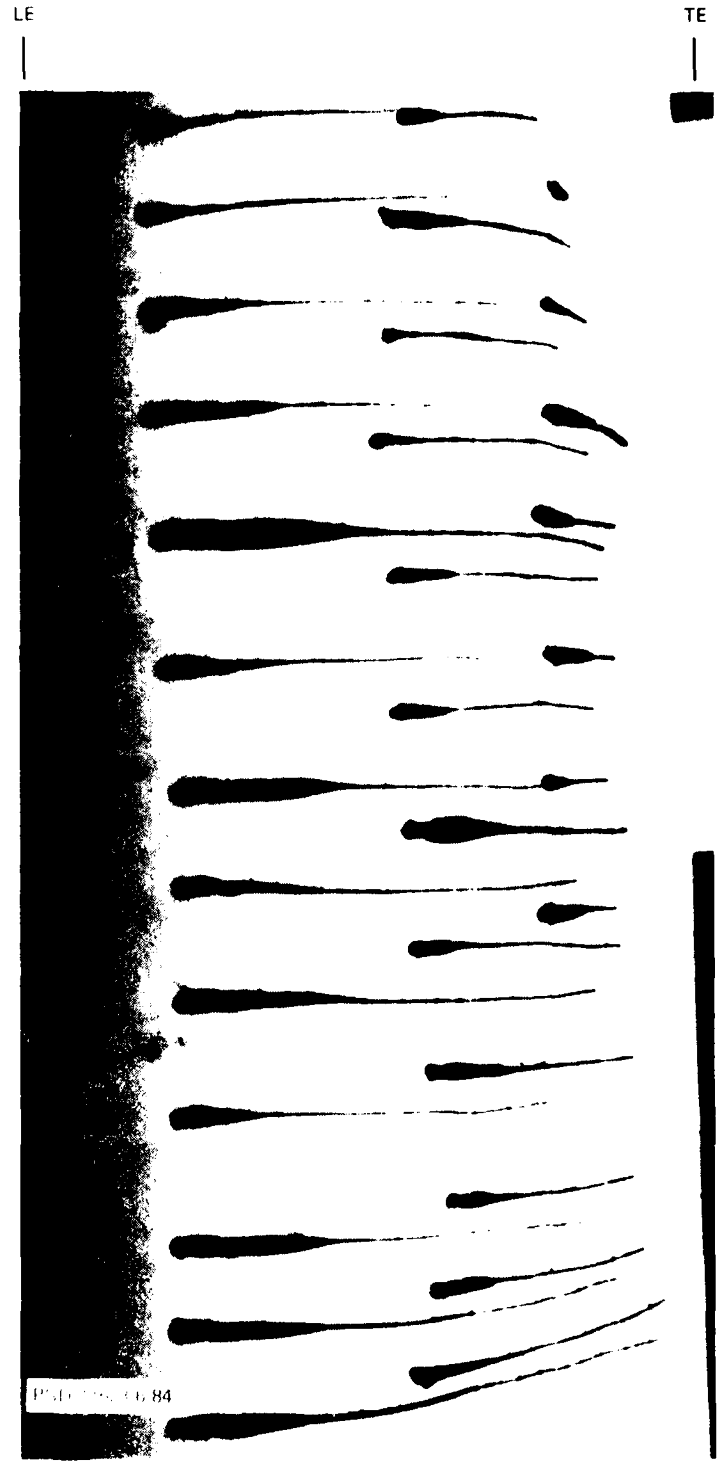


Fig. 5d. Silicone fluid (10,000 cSt) with 10:10 lampblack on oil-based enamel.

Fig. 5. (Continued)

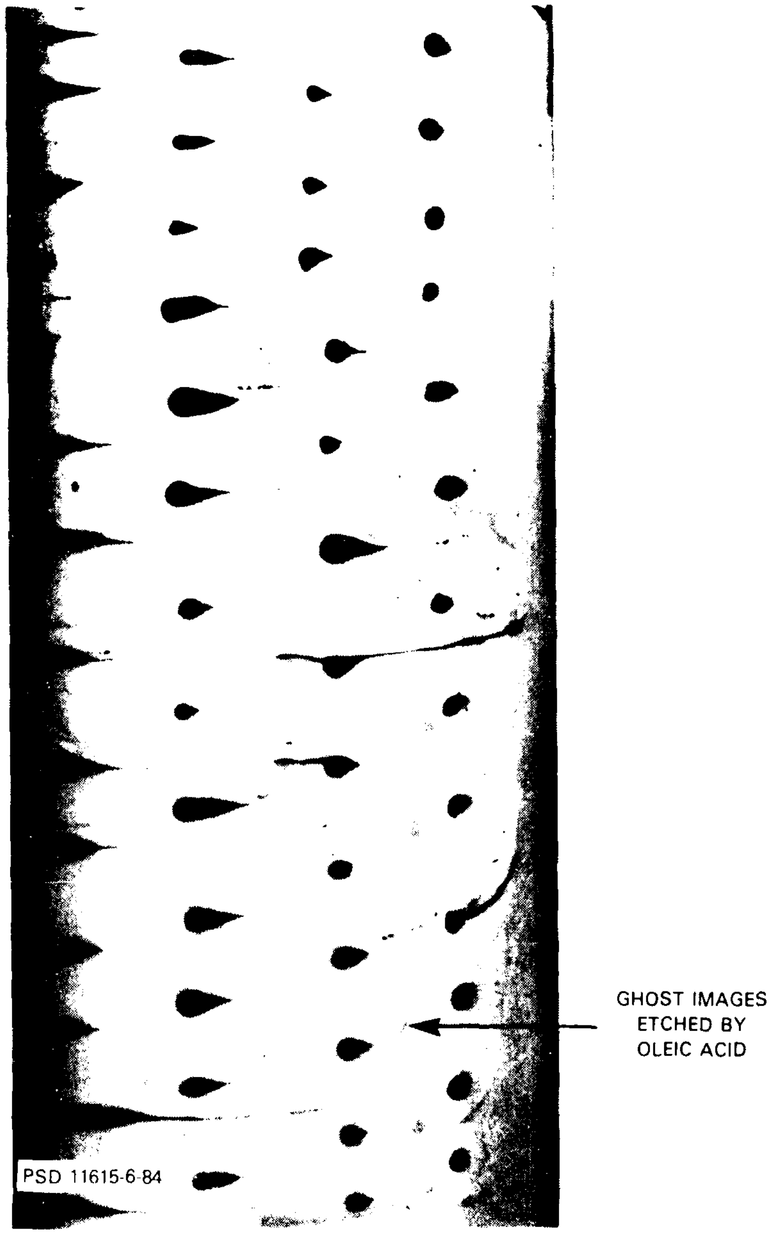


Fig. 5e. Silicone fluid (100 cSt) with 10:16 lampblack on oil-based enamel.

Fig. 5. (Continued)

or made application of properly shaped dots impossible. Thus viscosity increases using the present fluids, pigment, and paints do not lead to a fluid which can resist elongation at the much higher speeds typical of propeller blades.

The above observations were made during incremental speed increases, between which pauses of several minutes occurred. One attempt was made to raise speed rapidly to its maximum value. Fluids of oil and pigment in a 10:10 ratio and silicone (10,000 cSt) and pigment in a 10:2 ratio were used. The oil produced a normal, highly tapered group of trails. The silicone fluid was completely unsuccessful in that the trails were extremely wide, up to more than twice the dot diameter, and overlapped other trails before reaching the trailing edge. These trails were formed quite rapidly at some high speed which was not noted; until the rapid elongation, the silicone dots merely deformed in shape but did not extend. The oil dots, by contrast, had formed long trails well before the silicone dots had extended. Although this single observation does not represent an exhausive study, it implies that rapid increases in flow speed may not be a means for achieving resistance to premature elongation.

Fluid Mobility During Elongation

The term mobility refers qualitatively to the tendency of a dot fluid to flow downstream under low levels of skin friction. A highly mobile fluid forms a very long trail, along which fluid continues to flow over a long period of time, often building up a pool of fluid at the aft end when the trail encounters a separation line.

The tested fluids fell into two groups: highly mobile (oleic acid and oil) and of low mobility (silicone fluid and fluorinated ether). Oleic acid clearly showed the greatest response to low skin friction. Figure 5 indicates that dot trails of oleic acid entered the separation region at the trailing edge, and flowed transversely in that region. The transverse flow was caused by the pipe located aft of the model. Oil pigmented in a 10:10 ratio produced a similar transverse flow, but considerably less extensive. None of the other fluids were sufficiently mobile to enter the separation region.

Oleic acid furthermore showed its extraordinary mobility in other ways. For one, multiple trails were common: as many as five trails emanated from single dots. Multiple trails usually formed aft of short, untapered elongations; well-tapered trails did not usually produce more than one trail. Secondly, even extremely small dots produced extremely long trails. Such trails were extremely narrow, and often were not pigmented more than 1 in. (25 mm) aft of the dot, even though unpigmented, transparent lines of liquid were visible (although not photographable) for up to nearly 2 in. (50 mm) aft of the dot. Lastly, oleic acid produced the largest buildup of fluid at the aft end of the trails. This buildup tended to increase over time, indicating continuing flow. Oil, the second most mobile fluid, also built up a significant pool of fluid at the aft end of most trails.

The lower-mobility fluids, silicone and fluorinated ether, tended to produce shorter trails without pooling at the aft end. Two of these fluids had high viscosities, but the exception (100 cSt silicone) showed that viscosity of the base fluid was not exclusively responsible for the difference in behavior. However, the 100 cSt silicone fluid was somewhat variable in its behavior, including the production of a high proportion of unextended dots, perhaps showing greater sensitivity to the amount of pigment added. This fluid on one occasion produced long trails and several multiple

trails from a number of dots. It appears that extremely high pigmentation produces a low-mobility fluid, but at the risk of adding too much pigment and producing a poorly behaving fluid.

This conclusion is supported by the consistent performance of the fluorinated ether which had an intermediate viscosity. This fluid produced medium-length trails (see Figure 5) over a wide pigment range (8 to 14 parts of pigment per 10 parts of fluid) although the more heavily pigmented dots were not as well shaped.

These observations suggest that optimum versions of both low- and high-mobility dot fluids can be formulated as follows (for medium-speed flow). High-mobility fluids should use 50 to 100 cSt fluid with 2 parts of pigment to 1 part of fluid by volume. Low-mobility fluids should use 1,000 cSt fluid with equal volumes of pigment and fluid.

Mobility differences lead to differences in the way the fluids might be used. A high-mobility fluid could cover a large surface area with directional information on skin friction using a modest number of dots. Resulting patterns would say little about skin friction magnitude. A low-mobility fluid might serve to provide comparative information on skin friction magnitude as well, in terms of trail length. In this latter case, a large number of small dots should be applied to achieve maximum resolution.

Practical Considerations

Table 3 indicates that in many respects the various fluids were roughly equivalent. Even the amounts of pigment added showed similar dependencies on viscosity and elongation speed. It is evidently possible to produce useful skin friction patterns with all of the fluids.

However, the fluids showed interactions with the paints used, and potentially with facility materials, which should be considered in choosing a dot fluid. These interactions are summarized in Table 3.

Two fluids, oil and oleic acid, will permanently mark certain paints. The oil-lampblack mixture, used on epoxy enamel, left dark stains which could not be washed off with strong liquid detergent. No such stains occurred on oil-based enamels. Oleic acid etched the surface off both epoxy and oil-based enamels. These etched patterns are visible in Figure 5e. Although no pigment was deposited, the etched areas on the oil-based enamel caused changes in direction of subsequent trails (also visible in Figure 5). Thus, only acid-resistant surfaces should be used with oleic acid to permit several consecutive flow patterns to be obtained without having to repaint (unless, of course, permanent patterns are desired).

A third fluid, fluorinated ether, did not perform well on epoxy enamel which had been lightly sanded with very fine sandpaper. The sanding left many small roughness patches surrounded by smoother, unsanded paint. The dot trails on this surface were not continuous, but rather composed of discontinuous streaks of pigment with unpigmented gaps in between them. Close inspection showed that pigment was present where the surface was unsanded, but did not have pigment in sanded, less glossy areas. Tests on unsanded epoxy enamel confirmed that smooth, continuous trails form if the original painted surface is unaltered. Consequently, sanding to remove surface protrusions should not be done when using fluorinated ether. A similar but less strong effect occurred with oil, suggesting that sanding is generally not advisable.

As a final comment, both oleic acid and oil have effects which could be detrimental to various materials which may be present in facilities. Oleic acid is a moderately strong acid which can attack unprotected metals. Motor oil has been observed to cause damage to rubber seals around drive shafts. At DTNSRDC, natural oils are not permitted to be used in certain facilities containing vulnerable rubber components.

Recommended Fluids

The choice should be based on the model surface material, facility limitations, and desired flow characteristics. To avoid having to change the type of fluid for each situation, it is recommended that either fluorinated ether or silicone fluid be used in both 100 cSt and 1,000 cSt viscosities. Silicone fluid is somewhat more susceptible to smudging than fluorinated ether. Manufacturers of both of these fluids claim excellent resistance to chemical interactions. Manufacturer data on effects of fluorinated ether on elastomers show generally small effects which vary some with the different elastomers.

OPTICAL TECHNIQUES WITH COMPLIANT COATING

In this approach to flow visualization, a thin layer or coating of foam rubber is fastened to a surface. Flow impinging on the surface causes local deformations on the coating corresponding to the distribution of pressure (compression or expansion) and skin friction (shear). It was hypothesized then that the extremely sensitive optical techniques of holography and speckle photography might produce visible patterns of the deformations, thus mapping quantitatively the hydrodynamic forces acting on the surface. This approach was evaluated in the following way.

COMPLIANT COATING MATERIALS

Several closed-cell foam rubber materials were obtained and evaluated for use as coatings. Closed-cell foam rubbers have entrapped air and do not allow water to enter the interior. The pressure differential between the fluid and the entrapped air results in local compression of the foam. Neoprene foam rubber, available in convenient 1/8-in. (3.2 mm) thick sheets, was found to absorb some water and, hence, was only partially closed-cell. Polyethylene foam rubber, available in a larger thickness (1/4-in. (6.4 mm)), was found to absorb virtually no water under the fraction of an atmosphere of applied pressure used. These materials were painted flat white for the optical tests. The density, compressive Young's modulus, shear modulus, and compressive bulk modulus were measured from samples and the results summarized in Table 4.

The foam rubber coatings were attached to the steel model with rubber-to-metal cement. The cement made an excellent bond with the neoprene, which held up under the most severe 14.6 knot (7.5 m/s) flow conditions. The polyethylene was adequately attached to the model at moderate flow rates (7.1 knots (3.7 m/s)). However, at 14.6 knots (7.5 m/s), the cement failed at the trailing edge and only remained attached from the midchord to the leading edge. The polyethylene foam remained intact although it did produce an audible fluttering in the flow.

Table 4. Compliant coating material properties.

	Neoprene	Polyethylene
Thickness (in.)	0.125	0.25
Color	black	gray
Density (lb/ft^3)	8.5	1.8
Young's Modulus (lb/in^2)	52	117
Shear Modulus (lb/in^2)	17	39
Bulk Modulus (lb/in^2)	23	21

HOLOGRAPHY TECHNIQUE

Holography is a coherent optical technique requiring a laser. For these tests, a 4-watt argon-ion laser was used. Since this is a class IV (most dangerous class) laser, safety precautions were installed in the viewing shed where the laser and optical components were housed. A switch and shutter system was constructed so that the laser light was interrupted when the door to the viewing shed was opened. This protected personnel from unexpected exposure to laser light. All of the other openings in the viewing shed as well as the exterior windows of the ater tunnel were optically sealed. The optical components were attached to a rigid table top which was supported at model level by a specially designed table. Because of the limited space in the viewing shed, the table had to be assembled in place. To reduce the effects of ambient vibration on the optical components, the table top was isolated from the table by a damping material. The clarity of the water was adequate. The viewing window was made of single-thickness acrylic plastic, which proved to be entirely satisfactory.

The following optical arrangement was used to make holograms. The laser light was split into two beams by a variable intensity beam splitter. One of the beams, the object beam, was expanded by a lens to illuminate the model inside the water tunnel. Some of the scattered light exited the tunnel to expose the holographic plate (a very high resolution photographic film plate). The second beam, the reference beam, was redirected by mirrors and then expanded by a lens to also illuminate the holographic plate. A hologram thus results from the interference of these two wave forms. Figure 6 is a schematic of the optical arrangement. An electronic exposure meter controlled a shutter to properly expose the hologram. The exposed holographic plate was then developed by a photographic process. The holographic image can be reconstructed (i.e., observed) by illuminating the hologram with laser light from the same direction as the reference beam. An image-plane hologram was also made. The set-up was the same as in Figure 6 but with the addition of a lens placed between the model and the holographic plate. Thus, an image of the model could be focused on the film plate.

Holographic displacement analyses can be performed from a double-exposure hologram. One exposure would be made at zero or a low tunnel speed and a second exposure at a high speed. When the hologram is viewed, a series of fringes appear on the holographic image of the model. The fringe pattern is related to the three-dimensional displacements of the model's surface. Hence, holography can be used to determine the compression or expansion of the coating material and therefore the

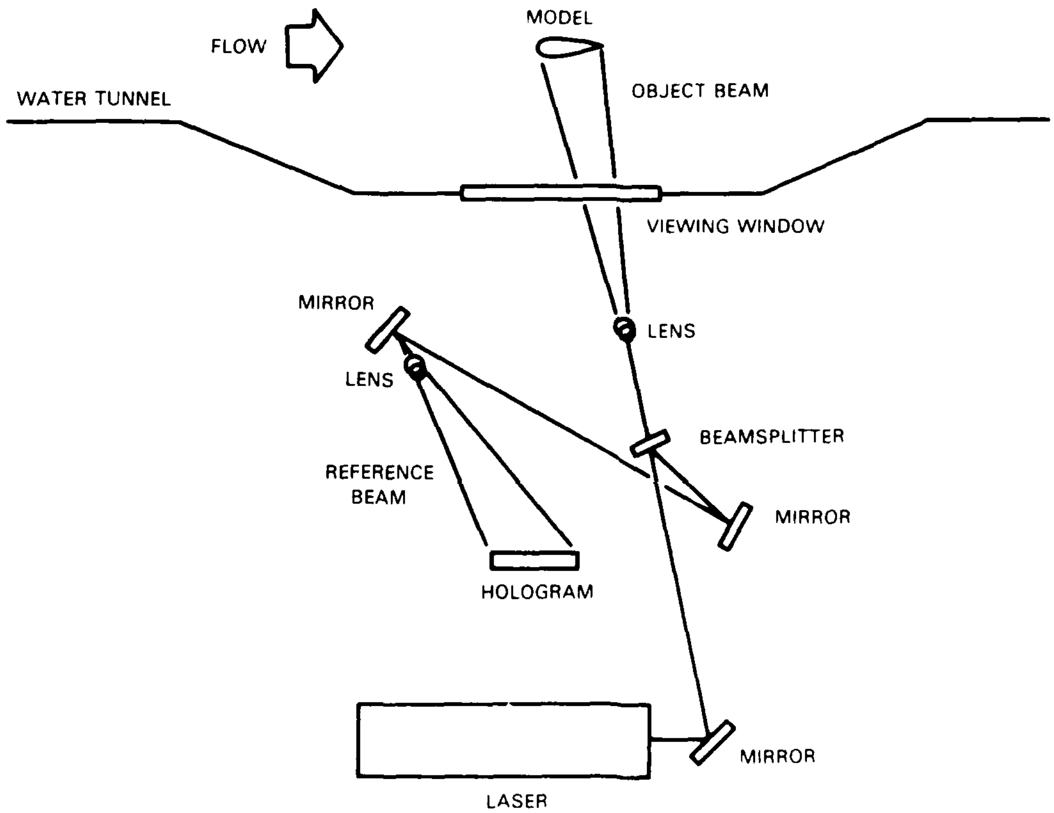


Fig. 6. Optical setup for holographic analysis.

pressure distribution on tthe surface of the model. Displacements, primarily those normal to the plane of the film, from ten up to a few hundred microinches, can be measured using holography.

In order to form a hologram, the relative motion between each of the optical components and the model should be less than a quarter wavelength of the light (approximately 5 μin or 0.1 μm) during the exposure time. Each exposure was typically about 5 s long. Low levels of motion are generally achieved by attaching the model and the optical components to a common surface, e.g., a rigid table top. The table top is then isolated from the ambient vibrations transmitted through the floor. In this case, the optical components were fixed to the table top but the model was located inside the water tunnel. The model was bolted to the hatch cover at the top of the tunnel. It was hoped that the massiveness of the water tunnel mounted on bedrock would be a sufficiently stable system.

This was found not to be the case. When a hologram was made, the image of the model did not reconstruct, although the optical components on the table top did. Thus, the table top itself was sufficiently rigid and isolated from vibrations. A target placed on the viewing window also failed to reconstruct as an image in the hologram. Another unsuccessful attempt resulted from attaching the holographic plate to the viewing window.

To quantify this vibration problem, electronic measurement techniques were employed. Although the instrumentation could not be fastened directly onto the model, vibration transducers were attached to both the eye bolt on the hatch cover (from which the model was supported) and the viewing-window housing. Vibrations were measured in the vertical direction, in the flow direction, and horizontally across the flow. The measured vibration levels were similar at both locations and for all three directions. A response of about 0.001 in. (0.025 mm) amplitude was found at 55 Hz when the tunnel was operating at full speed. However, these vibrations were not measurably excited at low or even moderate tunnel speeds. Hence, the operating vibration levels were probably not a problem. A much larger, low-frequency response of nearly 0.002 in. (0.05 mm) was encountered in the 0- to 3-Hz range. These vibrations were essentially independent of the tunnel speed, and were even recorded at zero speed. The water tunnel was apparently responding to ambient vibrations from the building. It was these low-frequency responses which interfered with the optical techniques. Since the vibrations occurred in all three directions and at zero speed, the prospect of isolating a model from them is not good.

Another approach to making a hologram when such large vibration levels are present is to reduce the exposure time. This can be done by using a high-energy pulsed ruby laser with exposure times of less than 20 n. Thus, holograms can be made of rapidly moving or rotating objects. Pulsed ruby holograms for displacement analysis can be formed using either of two techniques. In one technique, a pulsed ruby laser can be double-pulsed so that two exposures are generated up to a millisecond apart. If the forces acting on the model can be varied that quickly (such as by a shock wave or impulsive force) and displacements are in the 20 to 200 μin. (0.8- to 8-μm) range, then a holographic fringe pattern will result and a displacement analysis can be performed. The second technique would be to make each exposure with the model in the same relative position, except for the desired deformations. Thus, the holographic fringe pattern would only correspond to the displacements for which an analysis was desired. Unfortunately, neither of these conditions occurred in

the current tests. For the first case, the tunnel speeds could not be changed quickly enough (in a millisecond). For the second case, the large amplitude of the random vibrations would likely preclude the formation of a fringe pattern.

In addition to the vibration problems, an aspect of the hydrodynamic flow itself is expected to interfere with holography. The rapidly fluctuating transition line observed with liquid crystals causes large variations in shear stress (at least a factor of three) in the transition region. Interfering fringes would certainly not occur under these conditions. The effect of shear stress fluctuations in the fully turbulent boundary layer is not known, but difficulties in observing displacements appear possible.

It is concluded that holography is not a viable technique for observing compliant coating deflections under typical model test conditions.

SPECKLE PHOTOGRAPHY TECHNIQUE

Speckle photography is similar to holography in that an interference pattern is formed using coherent, laser-generated light. However, since the interference pattern is produced by diffraction of light by displaced but otherwise identical speckle patterns, it is possible to observe much larger displacements than is possible with holography, which generates interference patterns by shifting reflected light patterns extremely small distances, on the order of a wavelength of light. One source[7] estimates that speckle photography is practical for displacements of about 4000 to 60,000 μin (0.1 to 1.5 mm), in a plane parallel to the film plane. This type of deformation would be produced by flow-induced shear stress.

Based on an estimated maximum value of skin friction equal to 1.0 lb/ft^2 (48 Pa) occurring in the transition region, the maximum in-plane deflection of both rubber coatings was about 50 μin (1.3 μm). Unfortunately, this value is well below the practical range for speckle photography. The following unsuccessful result corroborates this prediction.

Attempts to produce specklegrams employed the optical arrangement shown in Fig. 7. Laser light was expanded by a lens to illuminate the model inside the water tunnel. Another lens then focused the image of the model onto the film (the same high-resolution film plates used in holography). After exposing the film at two different tunel speeds, the plate was developed. The resulting specklegram thus looked like a conventional photographic negative.

In one analysis approach, a specklegram is viewed by passing a narrow laser beam through the specklegram. A circle containing a series of equi-spaced parallel fringes (Young's fringes) is projected along the axis of the laser beam. The fringes can be viewed on a screen set normal to the light axis. Displacements of the object in the film plane are related to the direction and spacing of the Young's fringes. Hence, a specklegram can in principle be used to determine the shearing of the coating on the model's surface.

Photographs of the model hydrofoil were produced and viewed in the above manner. The film plates had images of the model, but the images did not produce meaningful fringe data. There were two reasons for this result. The model vibrations, although nearly large enough in amplitude to produce specklegrams, were random rather than periodic character and thus were unable to produce interfering speckles. In addition, the coating displacements were too small to yield speckle fringes. Since

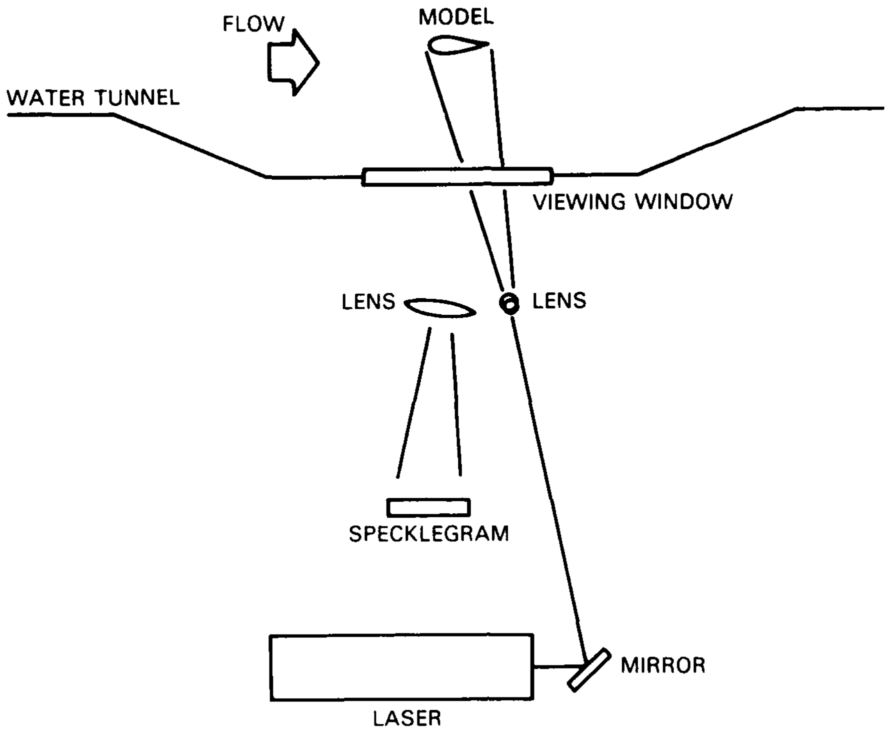


Fig. 7. Optical setup for speckle analysis.

the problem of small displacements would prevent this technique from succeeding under nearly all practical conditions, it is concluded that speckle photography cannot detect flow-induced displacements of compliant coatings.

CONCLUSIONS

1. Liquid Crystal Coatings: Several formulations of liquid crystal can provide extremely high-resolution visualization of skin friction patterns, both steady and time-varying, on surfaces exposed to moderately high-speed water flow (in the range of 5 to 15 knots (2.6 to 7.7 m/s)).
2. Fluid Dot Technique:
   a. Increases in viscosity of the base fluid do not provide a means of achieving resistance to premature dot elongation at speeds above 11 knots (6 m/s). For speeds below this level, some improved resistance can be obtained in this manner.
   b. High- and low-mobility fluids, which may correspond to low- and high-viscosity fluids, respectively, offer means for studying skin friction direction (high-mobility) or magnitude (low-mobility).
   c. Some fluids interact unfavorably with paints commonly used on model surfaces.
3. Compliant Coatings: Conditions typically present in hydrodynamic flow faciltiies, including ambient vibration and unsteady flow effects, prevent successful use of holography and speckle photography to measure flow-induced displacements of compliant coatings.

RECOMMENDATIONS

1. Liquid Crystal Coatings:
   a. It is recommended that liquid crystal coatings be used on a routine basis in small-scale hydrodynamic experiments to establish boundary-layer characteristics. Application should be by aerosol spray to minimize the amount of material that is washed off the model, potentially contaminating the water.
   b. Qualitative and quantitative correlations should be made between liquid crystal color patterns and shear stress distributions measured on one or more hydrodynamic surfaces. Comparisons should include calculated and observed transition and separation locations on the present test model.
   c. Further development of liquid crystal formulations should be pursued with the objective of producing coatings which are more resistant to loss of effectiveness over time, and are effective at the higher speeds typical of propeller blades.
2. Fluid Dot Techniques: Further experiments should be made with low viscosity (100 cSt) fluids, including fluorinated ether and silicone fluid, to determine whether high-mobility behavior similar to that of oleic acid and oil can be obtained with non-reactive base fluids.

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APPENDIX

EXISTING HYDRODYNAMIC FLOW VISUALIZATION TECHNIQUES FOR SURFACES

SHEAR STRESS DIRECTION

Oil Dots and Film

A summary of existing techniques for indicating shear stress direction in water is given in Table 5. The technique of choice is clearly oil dots. Work on propellers and, to a lesser extent, ship hull models has established that oil dots, in particular, are even more effective in water than in air. In water, in regions of relatively high skin friction, an oil drop elongates into an extremely narrow tail which may extend several inches downstream, as illustrated in Figure 8.[8] The extension is usually terminated by a relatively large pigment particle which apparently has been dragged downstream until the supply of oil and/or pigment has been exhausted. These trails may be as small as 0.01 in. (0.25 mm) in width. Such trails also arise when a band of oil is applied, or flows prematurely, in a direction transverse to the flow of interest. The pigment particles emerge from the band and move downstream, producing a row of closely-spaced narrow trails. Oil mixtures used at DTNSRDC include 10-, 30-, or 90-weight motor oil with sufficiently large amounts of added pigment to make the mixture quite viscous. Pigments used are lampblack, titanium oxide, and fluorescently dyed powders.

Table 5. Existing techniques.

Quantity	Type	Deficiency
Shear Stress Direction		
Oil dots, oil film	Semi-permanent	Premature response
Lead acid paint	Permanent	Low resolution Recycle time Safety
Tufts, minitufts	Transient	Low resolution
Flow flags	Transient	Low resolution
pH paint	Transient	Low resolution
Shear Stress Magnitude		
Oil dots, oil film	Semi-permanent	Low resolution Premature response
Oil film interferometry	Semi-permanent	Poor longevity in water
Pressure		
Reactive laminate	Permanent	Limited range

Fig. 8. Oil dot pattern obtained on a *propeller blade* at $R_n(0.7\ \text{span}) \sim 1$ million. Fluorescent pigment on a black *anodized* surface photographed under ultraviolet light. (Photo from Ref. 8).

The principal deficiency of oil dots is the tendency to respond prematurely to flow during acceleration to and, to a lesser extent, deceleration from, the flow condition of interest. Although misinterpretation of the resulting patterns can be minimized by observing the model during periods of changing flow, the tendency toward off-speed response clearly detracts from the technique's value.

Lead-Acid Paint

Lead-acid paint is a method of producing permanent streaks along skin friction lines on painted model surfaces. This approach involves handling of extremely noxious chemicals and the use of lead-based paint, both of which are undesirable (the paint may not be available in the future). Its use is apparently limited to DTNSRDC.

A specially prepared fluid is injected so as to contact the surface of a model which had been coated with white-colored lead-pigment paint. A dark brown streak is produced over a distance several feet downstream of the injection port.

Preparation of the injection fluid must be done in a well-ventilated area and by personnel wearing protective clothing. First, gaseous hydrogen sulfide (H_2S) obtained from pressurized bottles is bubbled through water until the water becomes cloudy. This solution is then mixed with hydrochloric acid (HCl) in a ratio of 4 parts H_2S solution to 1 part HCl.

It is believed that the brown stain produced when the fluid and paint react is lead sulfide (PbS), which remains fixed in the paint coating. Other byproducts such as hydrogen, chlorine, and water disperse into the towing facility. The model must be repainted to produce a new pattern.

Unfortunately, no replacement for this technique has been found which eliminates the chemical problems. Since the alternative permanent technique is oil dots, it is suggested that oil be injected through the ports otherwise used to inject acid. In this way the problem of oil's premature response would be avoided.

Tufts and Minitufts

Tufts give a fairly well-resolved coverage of surface skin friction direction when applied in large numbers as minitufts. Although originated by Crowder[9] for use in air, minitufts have more recently been used in water by Steinbring and Treaster[10] and at DTNSRDC. The Steinbring and Treaster paper presents many helpful suggestions for employing minitufts in water.

No improvement to the minituft method was produced in the present work. This method should be considered as a useful, moderate resolution FV technique.

Flow Flags

Flow flags are miniature rudder-like vanes supported on shafts which penetrate a model hull through special fittings. Pointers on the inboard end of the shafts are used to read orientation angles visually and record them manually. Fabrication of these devices is described in DTNSRDC drawing E-1407-1 entitled "Bilge Flow Flags." The cost of installation, effort in recording data manually, and relatively low resolution make these indicators rarely used in recent times, except for alignment of lifting surfaces such as submarine bowplanes with off-body flow. Improvements in resolution would require installation of a larger number of smaller flags.

pH Paint

A promising technique involving a pH-indicator paint has been developed by Hoyt.[11] Transient colored streaks are left on the painted surface aft of ports from which a basic solution is injected.

It is noted that this technique, as represented by the phenolphthalein mixture, is quite effective in many ways.* Both transition and separation regions can be observed. Some indication of flow off of the surface is also obtained, as a result of colored streams emanating from particles of phenolphthalein embedded in the paint. These streams are smooth in laminar regions and irregular in turbulent regions. The paint coating is said to have negligible effect on drag, based on a number of experimental comparisons. Also, the indicator-containing paint remains effective for subsequent experiments conducted even years later (although color traces vanish when injection stops and must be photographed during testing). In view of these excellent characteristics, this technique is probably underused, perhaps because of ignorance of it. Low resolution is the principal deficiency with this technique.

SHEAR STRESS MAGNITUDE

Oil Dots and Film

Some indication of shear stress magnitude, in relative terms, is obtainable from oil patterns. However, interpretation of oil streak lengths and eroded oil film regions yields little resolution of differences in skin friction. An improvement in this regard would require a coating which would, for example, lose part of its thickness in a highly detectable manner. Such a technique might be an erodable paint, which could be applied in thin, different-colored layers. A second, existing approach for such a detailed thickness measurement is described in the following section, but was not found feasible for use in typical facilities.

Oil Film Interferometry

Use of a thin oil-film to indicate skin friction magnitude by interferometric measurement of thickness, developed by Tanner in air, has also been shown to work successfully in water.[12] This work also described applicability of the technique to curved surfaces, three-dimensional flow, in pressure gradients, and under the effect of gravity (all in air). Generally, the technique can be corrected for the various flow complications, but it was found that the oil film must be inserted quickly into the water flow, and removed within a minute or two, or it begins to disintegrate. Furthermore, interferograms may not be possible while the coated surface is submerged; reported results were based on surfaces removed from water. Consequently, this technique may not be feasible for use in typical test facilities, since model removal is not quickly accomplished.

The oil-like fluid used by Tanner was silicone fluid. Successful application of the basic approach, although hindered by the interaction between this fluid, the water, and the model surface (which had to be water-repellent), might be possible using a different indicating fluid or a different liquid flow-medium. No evaluation or further development of this technique was pursued in the present work.

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*Hoyt, J.G., private communication.

PRESSURE INDICATORS

The only known pressure-distribution-indicating coating has been described by Okitsu and Aoki.[13] A laminated sheet containing two colorless chemical reactants which become red after reacting was used. One of the reactants was encapsulated in capsules which were broken by high pressures produced by cavity collapse on a cavitating propeller or turbine blade. The laminated sheet was cemented to the blade surface. Detailed measurements of color intensity were used to estimate cavity impact pressure distributions. This material requires relatively high pressures for activation, at least 10,000 lb/ft^2 (490 kPa). Pressure measurements using this technique are accurate within $\pm 10\%$. However, the extraordinary high pressure range in which this material acts makes it not feasible for subcavitating flow experiments.

Another possible visualization material is pressure-sensitive liquid crystal. However, consultations with chemists indicated that liquid crystals sensitive to pressure are effective only at very high pressures. Thus no candidate material was found.

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